

PATENT SPECIFICATION

(11) 1 449 289

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- (21) Application No. 59015/73 (22) Filed 20 Dec. 1973
 (31) Convention Application No. 7245585 (32) Filed 21 Dec. 1972 in
 (33) France (FR)
 (44) Complete Specification published 15 Sept. 1976
 (51) INT CL² G01N 23/203
 (52) Index at acceptance
 G1A 203 20Y 218 242 24Y 316 352 35Y 402 407 442 44Y
 452 45Y 478 482 504 505 506 510 514 518 611 753
 (72) Inventor BRONISLAV SEEMAN



(54) APPARATUS FOR STABILIZING THE GAIN OF RADIATION DETECTORS

(71) We, SCHLUMBERGER LIMITED, a Corporation of the Netherlands Antilles, having a principal place of business at 42 rue saint Dominique, 75340 Paris Cedex 07, France, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to apparatus for stabilizing the gain of radiation detectors and, more particularly, to apparatus for stabilizing the gain of detectors used in spectrometric applications, i.e. which have a response proportional to the received energy, such as scintillation detectors or junction detectors.

The invention is particularly applicable to the stabilization of the gain of photomultipliers used in the tools employed in petroleum prospecting for measuring the density of the geological formations traversed by a borehole.

It is known that density measurements in boreholes are made by means of a tool which comprises a gamma-ray source and a radiation detector, generally a scintillation detector, placed about 40 cm from the source. The rays emitted by the source lose their energy in the surrounding geological formation mainly by collision with electrons and some of them reach the detector which thus records a count rate which is smaller in proportion as the number of electrons per unit volume in the formation is high. The density of the formation, which is related to the number of electrons, may thus be determined from this count rate. Figure 1 shows, for three increasing values d_1 , d_2 and d_3 of the density, the energy spectrum, in semi-logarithmic coordinates, of the gamma rays reaching the detector, i.e. the curve giving the logarithm of the probability $N(E)$ of picking up a ray of energy E , as a function of this energy. This figure shows that the variations in density produce deformations in the part of the spectrum located below an

energy level E_0 (between 180 and 220 keV), but that above this energy level, there are no longer any deformations. The detected gamma rays having an energy higher than E_0 maintain, whatever the density, the same spectral distribution and their number is a decreasing exponential function of the density. Accordingly, at the output of the detector account is taken only of pulses having an amplitude higher than a given threshold, hereinafter called the normal count threshold S , which corresponds to detected gamma rays having an energy higher than E_0 . The recorded count rate thus furnishes the density measurement.

It is immediately apparent that in order for this technique to provide valid results, the gain of the detection system must be stable, i.e. a gamma ray of a given energy must always give rise to a pulse of the same amplitude. Any modification in gain in fact results in a shift of the spectrum and is equivalent to a shift in the threshold, thus leading to a modification in the count rate warping the density measurement. By way of example, Figure 2 shows three increasing values of the gain G_1 , G_2 and G_3 , the amplitude spectrum of the output pulses of the detector, i.e. the curve giving the probability $N(A)$ of obtaining a pulse of amplitude A , as a function of this amplitude. It is apparent that, if the count threshold A_0 has been defined for a value G_2 of the gain, an increase to the value G_3 is equivalent to lowering the threshold and consequently leads to the counting of more pulses. Conversely, a decrease in gain to the value G_1 is equivalent to raising the threshold and consequently leads to a loss of pulses.

It is known that detection systems and more particularly photomultipliers exhibit significant variations in gain due to the variations in temperature, and in the count rate itself. It is thus essential to provide a correction for these gain variations.

One approach to stabilizing the gain of photomultipliers has been to slave their

power supply voltage or the gain of the output amplifier to the position of a reference peak produced artificially, outside of the spectrum used for the measurement, by an
 5 alpha or gamma radiation source associated with the scintillator or by a very stable source of light acting directly on the cathode of the photomultiplier. More precisely, a signal is produced which represents the difference
 10 between the count rates recorded for two narrow energy windows chosen on the two edges of the reference peak. The gain variations of the photomultiplier, which result in a shift of the peak, and consequently in an unbalance between the two count rates, are
 15 thus represented by this signal which then acts on the value of the high voltage applied to the photomultiplier or the gain of its amplifier so as to always bring the peak to
 20 the same position.

Up to the present time, this approach has not been altogether satisfactory. In fact, if, in order to accurately detect any shift in the reference peak and thus be able to correct
 25 it quickly, use made of a high intensity source making it possible to have a low statistical noise, the measurements are disturbed by the presence of the Compton background related to this high peak. If, on
 30 the other hand, to prevent the measurements from being distorted by the Compton background, use is made of a low intensity source, producing a great statistical noise, the detection of gain variations will be less
 35 precise; their correction will be less rapid and the amount of time required will increase with the degree of disturbance.

In other words, a strong source gives a small statistical noise and thus assures a
 40 rapid correction, but disturbs the measurements; whereas a weak source does not disturb the measurements, but gives a large statistical noise, and, consequently, a slow correction. Because of this, it has hitherto
 45 been necessary to accept a compromise solution using a source sufficiently weak to avoid excessive disturbance of measurements, but sufficiently strong to avoid excessive slowness in the correction, mainly in the case of high
 50 variations in gain.

Accordingly, it is an object of the present invention to provide a gain stabilization technique allowing the use of a low-intensity source while maintaining a high speed of
 55 response to gain variations, this speed moreover being practically independent of the extent of these variations.

More precisely, according to the invention, an apparatus for stabilizing the gain of a
 60 radiation detector is provided, of the type comprising a radiation source capable of acting on the said detector to produce a reference figure in the spectrum of its output pulses, first means for detecting the displace-
 65 ments of this figure as a result of gain

variations and for producing a signal whose amplitude and sign are representative respectively of the extent and direction of the said displacements, and second means, sensitive to the said signal, for acting on the
 70 gain so as to correct these displacements, this apparatus being characterized by the fact that, to allow the use of a source of low activity without decreasing the speed of response to gain variations, it comprises third
 75 means, inserted between the said first and second means, for the amplitude modulation of the said signal according to a function of the said amplitude which is odd and which has a derivative which increases in absolute value from the origin, the signal thus modulated being the signal delivered
 80 to the second means to correct the displacements of the reference figure.

Thus, in the stabilization apparatus according to the invention, the signal representative of a deviation in gain undergoes, before being used to correct this deviation, an amplification whose absolute magnitude increases as the deviation increases. The apparatus thus
 85 tends to correct the variations in gain with a speed which increases as these variations increase, thereby compensating for the slowing effect due to the statistical error resulting from the use of a low activity source, which effect increases as the variations to be
 90 corrected increase. In this way, we obtain a response speed practically independent of the extent of the gain variations. The system to be balanced moreover exhibits, as will be shown further below, a low sensitivity to noise.

Advantageously, the modulation is accomplished according to the hyperbolic sine function, i.e. the signal used for the correction is proportional to the hyperbolic sine of the signal which represents the variations in gain.

Further objects and advantages of the invention will appear from the following
 110 description of advantageous embodiments, with reference to the appended drawings in which:

Figure 1 shows, in the case of a tool used for measuring density in geological formations, the effect of density variations on the energy spectrum of the detected gamma rays,

Figure 2 shows the effect of gain variations in the detector on the amplitude spectrum of the produced pulses,

Figure 3 is a schematic representation of a gain stabilizing apparatus according to the invention,

Figure 4 shows the reference peak produced in the amplitude spectrum of the pulses from the detector of this apparatus,

Figure 5 represents in detail the modulator of the apparatus of Figure 3, and

Figure 6 gives the response curve of this modulator.

Referring now to Figure 3, at 10 and 12 are shown respectively a photomultiplier and its scintillator which are used for detecting the gamma rays diffused by a geological formation 14.

The photomultiplier is supplied by a high-voltage source 16 whose level is adjustable by a voltage applied to a control input 18. The output pulses from the photomultiplier 10 are applied to the input of an amplifier 20, whose output is connected to the processing stage 22. This stage calculates the density of the formation 14 from the count rate of the received pulses.

The gain of the photomultiplier is stabilized:

—by a gamma source 24 built into the scintillator 12 and designed to produce a reference peak (Figure 4) outside of the spectrum of the pulses delivered by the amplifier 20, and

—by a device, designated generally by the reference 26, designed to detect the movements of the peak following variations in gain and to correct them by acting on the level of the high-voltage supply of the photomultiplier.

To prevent the disturbance of measurements, the gamma source 24 has a very low activity, a few μCi , and is naturally chosen so that the reference peak produced is clearly outside of the diffusion spectrum used for the measurement. By way of example, in a density logging tool in which the spectrum has mainly below 450 keV, use is made of a cesium-137 source of 2 μCi whose photoelectric peak is at 661 keV.

In the device 26, the pulses collected at the output of the amplifier are applied in parallel to three voltage comparators 28, 30 and 32 whose respective references are the amplitudes A_1 , A_2 and A_3 . Figure 4 shows how these three values are chosen. The amplitude A_2 corresponds to the summit S of the reference peak for a given gain to be kept constant, whereas the amplitudes A_1 and A_3 correspond to two corresponding points F and F' at the base of its edges. The vertical lines of these two points delimit, with the vertical line of S, two zones of equal area. Thus, the count rate N_1 of the pulses having an amplitude between A_1 and A_2 is equal to the count rate N_2 of the pulses having an amplitude between A_2 and A_3 . As an example, with a cesium-137 source having an activity of 2 μCi the count rate of the pulses having an amplitude between A_1 and A_3 is 200/s.

The outputs from the three comparators are applied to an anti-coincidence logic 34 comprising an inverter circuit 36, an AND gate 38, NOR circuit 40 and a flip-flop 42. The output of the comparator 30 is connected, through the inverter circuit 36, to an input of the AND gate 38 and to an

input of the NOR circuit 40. The output of the comparator 28 is connected to the other input of the AND gate 38 and that of the comparator 32 to the other input of the NOR circuit 40. Finally, the input R of the flip-flop 42 is connected to the output of the NOR circuit and its input S to the output of the AND gate. The output Q of this flip-flop is connected to the input of a low-pass filter 44. The latter is a RC filter whose cutoff frequency is 2 Hz for a source delivering, between A_1 and A_3 , a count rate of 200/s. The output of this filter is connected to the input 46 of a nonlinear modulator circuit 48 furnishing, at its output 50, a voltage V_s which is approximately proportional to the hyperbolic sine of the voltage V_s applied to its input 46. Finally, this modulator is followed by an integrating stage 52 whose output is connected to the control input 18 of the high-voltage power supply 16.

Figure 5 represents schematically an advantageous embodiment of the modulator 48. The latter consists of five branches 54, 56, 58, 60 and 62 connected in parallel between its input 46 and its output 50, and comprising respectively:

- a resistor 64 with a value R_1 ,
- a resistor 66 with a value R_2 and a diode 68, in series,
- a resistor 70 with a value R_2 and a diode 72, in series,
- a resistor 74 with a value R_3 and a diode 76, in series,
- a resistor 78 with a value R_3 and a diode 80, in series.

These four diodes are identical. The only difference between the branches 56 and 58 is that the diode 68 of the branch 56 is connected to the output 50 through its cathode, whereas the diode 72 of the branch 58 is connected through its anode. Likewise, the difference between the branches 60 and 62 is that the diode 76 of the branch 60 is connected to the output 50 through its cathode whereas the diode 80 of the branch 62 is connected through its anode. Finally, the diodes 72 and 80 have their respective cathodes connected to a voltage source $+V$, respectively through a resistor 82 having a value R_4 and a resistor 84 having a value R_5 , whereas the diodes 68 and 76 have their respective cathodes connected to a voltage source $-V$, respectively through a resistor 86 having a value R_4 and a resistor 88 having a value R_5 .

It is easy to establish that the potentials V_{A68} , V_{A72} , V_{K72} and V_{K80} respectively on the anode of the diode 68, the anode of the diode 76, the cathode of the diode 72 and

the cathode of the diode 80 are expressed, according to the voltage V_0 at the input 46, by the following relationships:

$$V_{A68} = \frac{V_0 R_4 - V R_2}{R_2 + R_4} \quad (1)$$

$$V_{A76} = \frac{V_0 R_5 - V R_3}{R_3 + R_5} \quad (2)$$

$$V_{E72} = \frac{V_0 R_4 + V R_2}{R_2 + R_4} \quad (3)$$

$$V_{E80} = \frac{V_0 R_5 + V R_3}{R_3 + R_5} \quad (4)$$

Under these conditions, and moreover assuming that the ratio R_2/R_4 is chosen lower than the ratio R_3/R_5 , we see that:

—as the input voltage V_0 increases from zero, the four diodes are first reverse-biased, and then the diodes 68 and 76 are forward-biased one after the other starting at $V_0 = V R_2/R_4$ and $V_0 = V R_3/R_5$ respectively; —as the input voltage V_0 decreases from zero, the four diodes are first reverse-biased, and then the diodes 72 and 80 are forward-biased one after the other, beginning at $V_0 = -V R_2/R_4$ and $V_0 = -V R_3/R_5$.

Therefore, through a suitable selection of the values R_1 , R_2 , R_3 , R_4 and R_5 , the circuit 48 can be given the response curve $i_s = f(V_0)$ shown in Figure 6, where i_s is the current applied to the input of the integrator. This curve represents approximately the function $i_s = k \cdot \sin h V_0$ formed by five straight-line portions A, B+, C+, B- and C-:

—The portion A corresponds to the range for which the four diodes are reverse-biased; the branches 56, 58, 60 and 62 containing these diodes thus have a very high resistance, so that the equivalent resistance of the circuit is substantially equal to R_1 .

—The portion B+ corresponds to the range for which the diode 68, then forward-biased, associates the resistor 66 with the resistor 64, so that the equivalent resistance of the circuit is substantially equal to

$$R_1 R_2 / (R_1 + R_2),$$

and thus lower than R_1 .

—The portion C+ corresponds to the range for which the diodes 68 and 76, both forward-biased, associate the resistors 66 and 74 with the resistor 64, so that the equivalent resistance of the circuit is substantially equal to

$$R_1 R_2 R_3 / (R_1 R_2 + R_1 R_3 + R_2 R_3),$$

and thus lower than R_2 .

—The portion B-, the negative counterpart of B+, corresponds to the range for which the diode 72, then forward-biased, associates the resistor 70 with the resistor 64, so that the equivalent resistance of the circuit is substantially equal to

$$R_1 R_2 / (R_1 + R_2).$$

—The portion C-, the negative counterpart of C+, corresponds to the range for which the diodes 72 and 80, both forward-biased, associate the resistors 70 and 78 with the resistor 64, so that the equivalent resistance of the circuit is substantially equal to

$$R_1 R_2 R_3 / (R_1 R_2 + R_1 R_3 + R_2 R_3).$$

Summarizing, therefore, as the input voltage V_0 increases, resistors of suitably chosen values are associated in parallel with the basic resistor 64 and, lowering thereby the equivalent resistance of the circuit, produce an increase in the coefficient of proportionality between the input and output signals, allowing the curve $i_s = f(V_0)$ to be assimilated with the curve $i_s = k \cdot \sin h V_0$.

As an example and approximately:

—The portion A extends from $V_0 = -4v$ to $V_0 = +4v$, with a slope of $0.4 \mu A/v$;

—The portion B+ extends from $V_0 = +4v$ to $V_0 = +8v$, with a slope of $1.5 \mu A/v$;

—The portion C+ extends beyond $V_0 = +8v$, with a slope of $7 \mu A/v$;

—The portion B- extends from $V_0 = -4v$ to $V_0 = -8v$, with a slope of $1.5 \mu A/v$;

—The portion C- extends beyond $V_0 = -8v$, with a slope of $7 \mu A/v$.

This is obtained with $R_1 = 1 M\Omega$, $R_2 = 380 K\Omega$, $R_3 = 70 K\Omega$, $R_4 = 540 K\Omega$, and $R_5 = 45 K\Omega$.

The operation of the apparatus of Figure 3 can now be described. It should first be stated that the output pulses from the amplifier 20, having:

—an amplitude lower than A_1 have no effect on the comparators 28, 30 and 32;

—an amplitude higher than A_1 , but lower than A_2 , trigger the comparator 28 but have no effect on the other two;

—an amplitude higher than A_2 , but lower than A_3 , trigger the comparators 28 and 30 but have no effect on the comparator 32;

—an amplitude higher than A_3 trigger the three comparators.

Consequently, the appearance at the output of the amplifier 20 of a pulse having an amplitude lower than A_1 or higher than A_3 is not felt by the logic 34. On the other hand, when a pulse having an amplitude between A_1 and A_2 appears, the two inputs of the AND gate 38 are at 1 whereas the inputs of the NOR circuit 40 are respectively at 1 and 0, the output of the AND gate

is thus at 1 but that of the NOR circuit is at 0, so that the flip-flop 42 receives at its input R a pulse which resets it. In the case of a pulse having an amplitude between A_2 and A_3 , it is, on the contrary, the inputs of the AND gate which are respectively at 1 and 0 whereas the two inputs of the NOR circuit are at 0; the output of the AND gate is thus at 0, but that of the NOR circuit is at 1, so that the flip-flop 42 receives at its input S a pulse which sets it.

With the output Q of the flip-flop 42 thus being reset by a pulse having an amplitude between A_1 and A_2 , and set for a pulse having an amplitude between A_2 and A_3 , the output level of the low-pass filter 44 is representative of the deviation between the count rates N_1 and N_2 of the pulses having an amplitude between A_1 and A_2 and between A_2 and A_3 , respectively. More precisely:

—if the gain keeps its reference value, for which the two count rates are equal, the mean output voltage of the filter is zero;

—if the gain increases and thereby produces a shift (toward the right) of the reference peak, corresponding to a decrease in N_1 and an increase in N_2 , the mean output voltage of the filter has a positive value proportional to the unbalance between the two count rates;

—if the gain decreases and thus produces a shift (toward the left) of the reference peak, corresponding to a decrease in N_2 and to an increase in N_1 , the mean output voltage of the filter has a negative value proportional to the unbalance between the two count rates.

It is this voltage which constitutes the voltage V_e applied to the input 46 of the modulator 48. The latter, operating as described hereinabove, thus provides at its output 50 a voltage V_s approximately proportional to the hyperbolic sine of V_e . The integrator 52, receiving this voltage, will thus apply to the control input 18 of the power supply 16 of the photomultiplier a continuous voltage to stabilize the gain at its reference value. More precisely:

—if no gain variation is detected, the mean voltage delivered to the integrator is zero and the high voltage applied to the photomultiplier remains unchanged;

—if a gain increase is detected, the mean voltage delivered to the integrator has a negative value proportional to the hyperbolic sine of the deviation between the two count rates; this voltage then makes the voltage applied to the photomultiplier decrease until this deviation is cancelled;

—if a gain decrease is detected, the mean voltage delivered to the integrator has a positive value proportional to the hyperbolic sine of the deviation between the two count rates; this voltage then makes the voltage

applied to the photomultiplier decrease until this deviation is cancelled.

Thus, a variation in the gain of the detection system is corrected by means of an error signal approximately proportional to the hyperbolic sine of the variation, i.e. (with the hyperbolic sine function having a derivative whose absolute value increases constantly from the origin) by means of an error signal proportional to the variation, the coefficient of proportionality itself being an increasing function of the variation. In other words, when a variation in gain is detected, the speed at which it tends to be corrected is proportional to the deviation. Now, it is known that, owing to the use of a reference source with a very low activity, the statistical error on the detection of gain variations has the effect of increasing the time necessary for their correction, this effect being proportional to the variations to be corrected. The apparatus according to the invention makes it possible to compensate for this phenomenon because, on the contrary, the speed at which it tends to correct the variations in gain is proportional to the extent of the variations. Thus, in spite of the use of a low-activity source, the speed of response to the variations in gain is considerably increased and maintains a value substantially independent of the extent of these variations.

By way of example, the apparatus of the invention reduces a disturbance of 100% to 1% six times faster than an apparatus of the same type not performing a modulation of the error signal.

It is moreover important to note that, in the absence of disturbance, the system functions in a small-slope zone of the response curve of the modulator; the input of the integrator is thus at a level near zero, which naturally confers upon the apparatus at equilibrium a low sensitivity to noise.

Of course, the correction of gain variations could be achieved by acting on the gain of the output amplifier of the detector instead of on the high-voltage power supply. In this case, the output of the integrator is connected to the amplifier gain control input.

WHAT WE CLAIM IS:—

1. Apparatus for stabilizing the gain of a radiation detector, of the type comprising a radiation source capable of acting on the said detector to produce a reference figure in the spectrum of its output pulses, first means for detecting the displacements of this figure as a result of gain variations and for producing a signal whose amplitude and sign are representative respectively of the extent and direction of the said displacements, and second means, sensitive to the said signal, for acting on the gain so as to correct these displacements, this apparatus being characterized by the fact that, to allow

the use of a source of low activity without decreasing the speed of response to gain variations, it comprises third means, inserted between said first and second means, for the amplitude modulation of the said signal according to a function of the said amplitude which is odd and which has a derivative which increases in absolute value from the origin, the signal thus modulated being the signal delivered to the second means to correct the displacements of the reference figure.

2. The apparatus of claim 1, wherein the third means consist of a non linear modulator circuit adapted to produce at its output a signal approximately proportional to the hyperbolic sine of the signal applied to its input.

3. The apparatus of claim 2, wherein the nonlinear modulator circuit comprises:

—2 $n-1$ resistors connected in parallel between its input and its output,

—first switching means associated with n of these resistors and adapted to switch in each of them at predetermined positive values of the input signal, and

—second switching means associated with n other resistors and adapted to switch in each of them at predetermined negative values of the input signal.

4. The apparatus of claim 3, wherein the first and second switching means comprise diodes in series with the associated resistors and connected so that those of the first means are forward-biased at the said predetermined positive values of the input signal and so that those of the second means are reverse-biased at the said predetermined negative values of the input signal.

5. The apparatus of any preceding claim, wherein, the reference figure being a peak, the means for detecting its displacements comprise:

—three voltage comparators which are connected to receive the pulses generated by the detector and whose references are the amplitudes corresponding respectively to the summit of the peak and to two corresponding points on its edges,

—an anticoincidence logic connected to the output of these three comparators and adapted to produce a signal with two states

which correspond to pulses from the detector having amplitudes between the amplitude of the summit of the peak and the respective amplitudes of the two corresponding points on its edges, and

—a filtering circuit connected to receive this two-state signal and adapted to produce a signal whose mean level and sign are representative respectively of the deviation between the durations of its two states and of the direction of this state.

6. The apparatus of claim 5, wherein the anticoincidence logic comprises:

—an AND gate one input of which is connected to the output of the comparator having the lowest reference,

—a NOR circuit one input of which is connected to the output of the comparator having the highest reference,

—an inverter circuit connected between the output of the comparator whose reference is the amplitude which corresponds to the summit of the reference peak and the other inputs of the AND gate and of the NOR circuit, and

—a flip-flop circuit whose set input is connected to the output of the AND gate and whose reset input is connected to the output of the NOR circuit, the said two-state signal being picked up at its output.

7. The apparatus of any preceding claim, wherein the second means comprise an integrating circuit connected to receive the amplitude modulated signal and whose output delivers a continuous signal used for correcting either the power supply voltage of the detector or the gain of an output amplifier connected in series with the output of the detector.

8. The apparatus of any of preceding claims, wherein the source is a cesium-137 source having an activity of a few μCi .

9. Apparatus for stabilizing the gain of a radiation detector, said apparatus being substantially as herein described with reference to Figures 3 to 6 of the accompanying drawings.

B. D. STOOLE,
Chartered Patent Agent,
Agent for the Applicants.

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COMPLETE SPECIFICATION

4 SHEETS

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Sheet 1

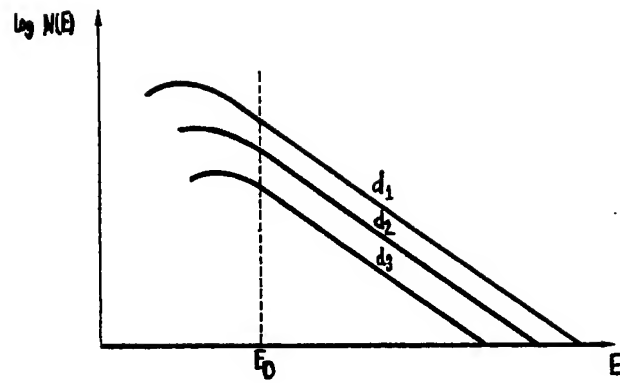


Fig. 1

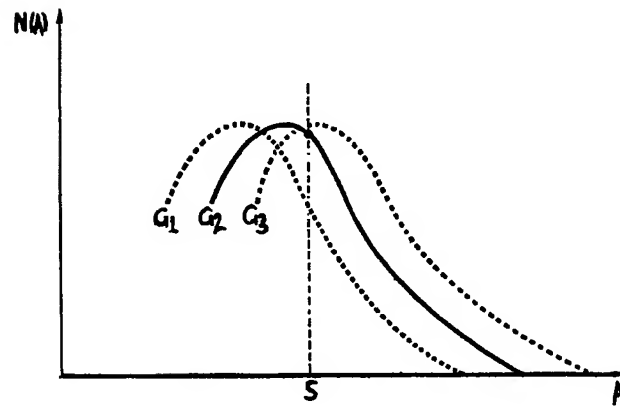
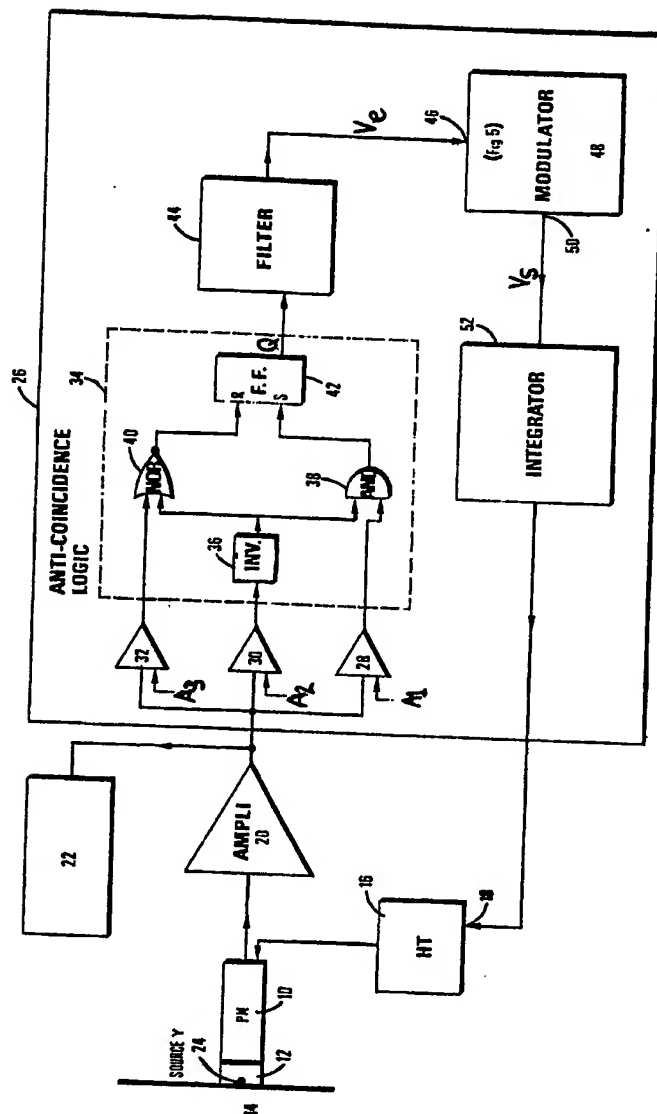


Fig. 2



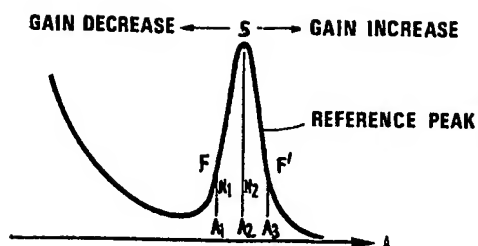


Fig. 4

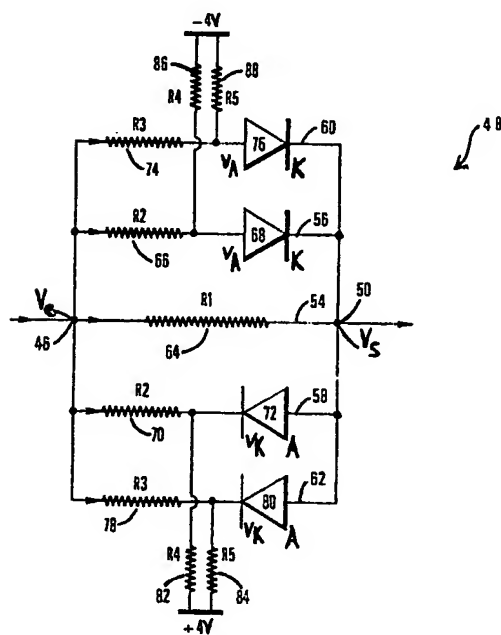


Fig. 5

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COMPLETE SPECIFICATION

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Sheet 4

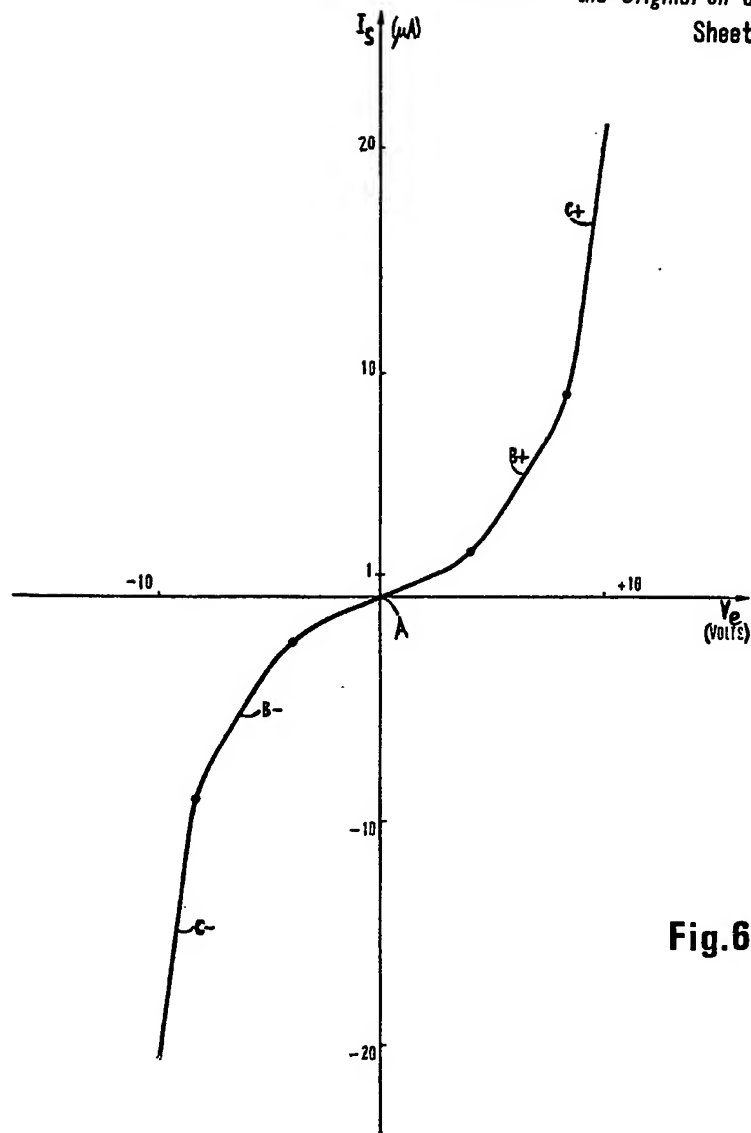


Fig.6